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Superconducting Multipole Corrector Magnet

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***Abstract*—A novel concept of superconducting multipole corrector magnet is discussed. This magnet assembled from 12 identical racetrack type coils and can generate any combination of dipole, quadrupole and sextupole magnetic fields. The coil groups are powered from separate power supplies. In the case of normal dipole, quadrupole and sextupole fields the total field is symmetrical relatively the magnet median plane and there are only five powered separately coil groups. This type multipole corrector magnet was proposed for BTeV, Fermilab project and has following advantages: universal configuration, simple manufacturing and high mechanical stability. The results of magnetic design including the field quality and magnetic forces in comparison with known shell type superconducting correctors are presented.**

***Index Terms*—Multipole, Superconducting, Magnet, Corrector, Racetracks.**

I. Introduction

Large number of different superconducting multipole correctors were designed and manufactured for Tevatron [1], UNK [2], RHIC [3], LHC [4]. Some correctors showed rather low mechanical stability, long training history and usually worked at 30-50% of short sample current limit. One of the problems is how to wind the shell type multiturn coil from 0.3-0.5 mm diameter superconductor without shorts and with precisely specified geometry. Correctors for Tevatron had a random windings, not precise geometry and as a result had a long training history [1]. Efremov Institute for UNK correctors initially used FNAL technology but coils had inner shorts as a result of damage an enamel insulation during collaring. Better results were achieved with a ribbon type cable and a single wire technique applying an additional turn fiberglass insulation. BNL for RHIC [3] correctors used the 5-axis computer controlled machine, which provided precise conductor positioning and fixation on support cylinders for each winding. Such technology is good for coils with low number of layers but is a labor consuming for multilayer coils. CERN for LHC [4] used a ribbon type cable with the number of splices to connect all ribbon wires in series. This technique simplify the winding process but needs to make a large number of superconducting splices to connect all wires in the ribbon type cable to form the coil.

That is why for FNAL BTeV [5] project was proposed the concept of multipole superconducting corrector (see Fig.1.) which simplify the magnet manufacturing technology and has several advantages discussed in the paper.

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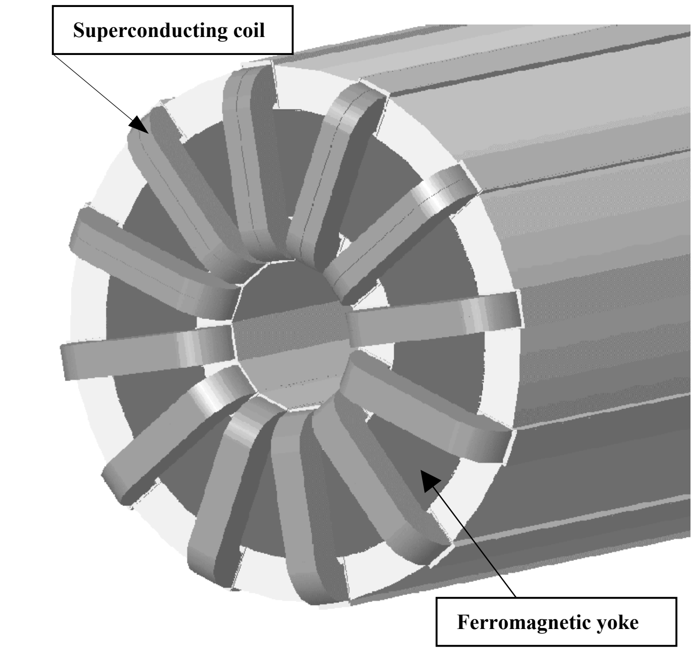

Fig.1. Superconducting multipole corrector end view.

II. Corrector Magnet Design

A. Magnet Parameters and Concept

New superconducting correctors for BTeV should have parameters shown in Table 1.

TABLE 1

Type	Trims	Integrated strength	Cold mass length
A	Horizontal (HD) and vertical dipole (VD) Skew quadrupole (SQ)	0.48 T*m 7.5 T	≤ 0.8 m
B	Horizontal and vertical dipole Skew quadrupole	0.48 T*m 7.5 T	≤ 0.8 m
C	Horizontal or vertical dipole Quadrupole Sextupole (S)	0.48 T*m 25 T 450 T/m	≤ 1.2 m

The main difference in BTeV case is that there will be only small quantity (~12) of correctors and the amount of superconductor has a very low influence on the total cost. At the same time the magnet reliability, low manufacturing cost of identical magnets with simple tooling is a preferable way of magnet optimization.

From this point of view the novel combined function multipole corrector (see Fig. 1, 2 and Table 2) should be taken under consideration.

TABLE 2

Corrector type	A	B	C
Integrated dipole field, T*m		0.48	
Integrated quadrupole gradient, T		25	
Integrated sextupole strength , T/m		450	
Effective length, m	0.8	0.8	1.2
Inner coil radius, mm		40	
Inner core radius, mm		63	
Outer core radius, mm		120	
Operational current, A		35 - 77	
Coil number of turns		760 - 1700	
Bare strand diameter, mm		0.3 - 0.5	
Max strand diameter with insulation, mm		0.43 - 0.63	
Coil area, mm^2		368	
Cold mass outer diameter, mm		300	

This corrector assembled from 12 identical racetrack type coils. All these coils are powered from separate power supplies and capable generate all types of superimposed dipole, quadrupole and sextupole fields. In the case of normal dipole, quadrupole and sextupole (Type C) the total field is symmetrical relatively the median plane and there will be only 5 powered separately windings. Such corrector is also very efficient to replace the combination of normal and skew fields by the main field, which is rotated by powering different coils.

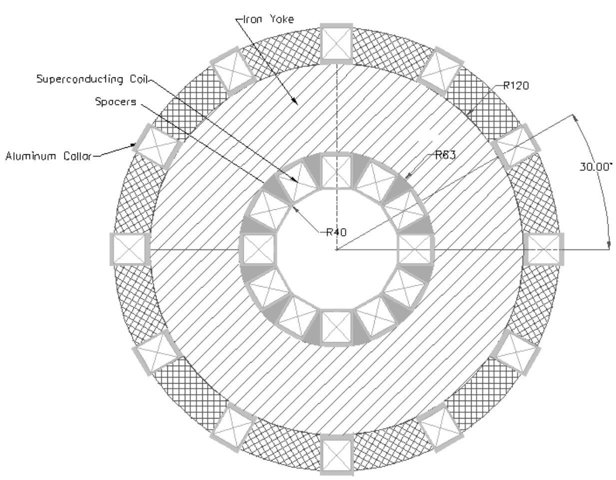

Fig. 2. Corrector magnet cross-section and structure.

The racetrack coil winding is very simple for manufacturing process. There are no problems to wind the coils with tension and provide prestress by using the aluminum shell shrinkage, which will press the coil to the low carbon steel core. The coil ends are very short and corrector is very effective in longitudinal direction. Such type of magnet can be assembled from 12 identical coil blocks and each of them can be separately tested in a small test cryostat with inner bore diameter 120 mm and length 1.2 m. The magnet cold mass can be easily repaired just by replacing a damaged coil. There are only coil joints with current leads and it increase the magnet reliability. It looks like that this corrector will need 2 times more superconductor than the shell type design. But proper comparison showed that the superconductor volume increase not so large because of more efficient combined function overlapping fields and lower maximum fields than for single function correctors distributed in radial or longitudinal direction.

B. *Magnetic Design*

The magnet has simple magnetic design. The combined function magnetic field is formed by 12 identical racetrack coils equally distributed with angular separation 30^o. The number of coils is chosen to provide the dipole, quadrupole and sextupole fields at minimum number of coils and reasonable field quality. The rectangular cross-section was chosen to simplify the winding process. In common case each coil can be powered separately from 50-80 A maximum current power supply. Usually correctors have reduced demands to the field quality because the corrector field errors can produce only second order effects. A proper programming of power supplies can eliminate also all field deviations caused by manufacturing deviations, iron saturation effects, etc. The current of each N coil is the sum of the dipole, quadrupole and sextupole components.

$$I_N = I_{ND} + I_{NQ} + I_{NS.}$$

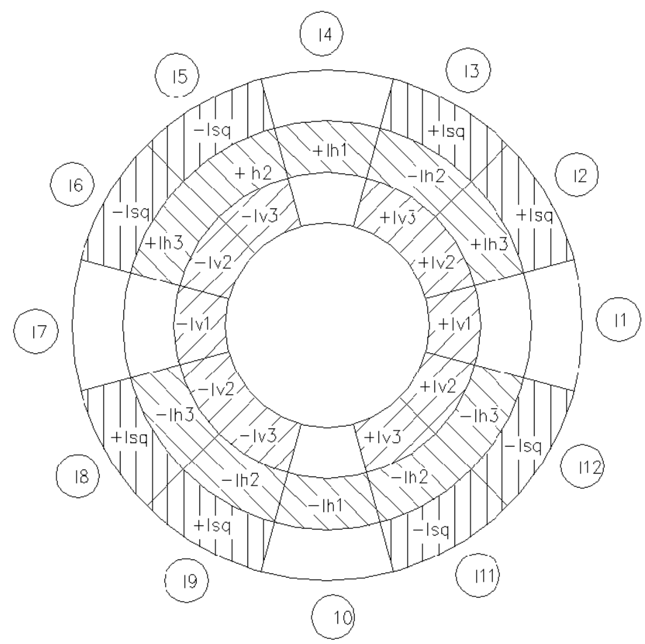

Fig. 3. Azimuthal diagram of coil currents distribution.

The dipole, quadrupole and sextupole current components were calculated by ROXIE [6] for each coil using field quality optimization procedure. The optimization results, iron saturation effects and fringing fields were calculated by OPERA 2D, Vector Field Corp.

The outer coil sections will produce the fringing field, which can be eliminated by 10mm thick outer magnetic shield. This shield can be also combined with the cryostat outer vacuum shell.

Another attractive option is to use these correctors as staying alone dipole or quadrupole or sextupole. The maximum magnet strength is limited by the iron core saturation. For example the dipole field can be easily increased with 50 A current in about 2.5 times at zero sextupole and quadrupole fields.

The type A corrector should generate horizontal and vertical 0.48 T*m dipole fields with the additional 7.5 T skew quadrupole. The corrector parameters are shown in Table 3 and the field harmonics at 25.4 mm reference radius are shown in the Table 4.

TABLE 3

Dipole field, T	0.6
Effective length, m	0.8
Dipole component ampere-turns, A	Iw_{d1} = 15200, Iw_{d2} = 13300, Iw_{d3} = 7600
Skew quadrupole gradient, T/m	9.375
Quadrupole component ampere-turns, A	Iw_q= 12100
Total coil ampere-turns at max field, A	33000
Maximum flux density in the yoke at max coil currents, T	2.3

TABLE 4

MAIN FIELD: -0.59781 NORMAL REL. MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	-0.02913	b 3:	0.00099
b 4:	0.00000	b 5:	-2.32043	b 6:	0.00221
b 7:	-0.55706	b 8:	0.00000	b 9:	-0.00070
b10:	0.00021	b11:	5.45721	b12:	0.00000
b13:	0.97713	b14:	-0.00001	b15:	0.00000
b16:	0.00000	b17:	0.00016	b18:	0.00000
b19:	0.00013	b20:	0.00000	b	

SKEW REL. MULTIPOLES (1.D-4):

a 1:	-10000.04258	a 2:	-3992.24722	a 3:	0.02127
a 4:	0.00000	a 5:	2.32912	a 6:	-0.00572
a 7:	-0.55691	a 8:	0.00000	a 9:	0.00071
a10:	10.88396	a11:	5.45699	a12:	0.00000
a13:	-0.97717	a14:	-0.31966	a15:	0.00000
a16:	0.00000	a17:	-0.00017	a18:	0.00000
a19:	0.00013	a20:	0.00000	a	

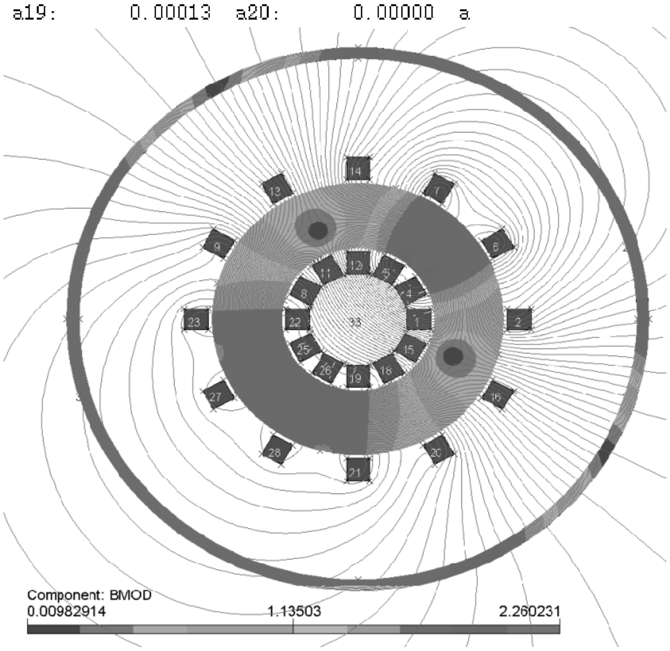

Fig. 4. Corrector A flux density distribution at maximum coil currents.

The corrector B should generate horizontal or vertical 0.48T*m dipole field with the additional 7.5 T skew quadrupole. All corrector parameters can be obtained from corrector A design with only one dipole field component. In this case the maximum coil ampere-turns are 25400 A and all other parameters as in the Table 3.

The corrector C should generate horizontal or vertical 0.48 T*m dipole field with the additional 25 T quadrupole and 450 T/m sextupole. The corrector parameters are shown in Table 5 and field harmonics in Table 6.

TABLE 5

Dipole field, T	0.4
Effective length, m	1.2
Dipole component ampere-turns, A	Iw_{d1} = 9856.2, Iw_{d2} = 7189, Iw_{d3} = 2650.9
Quadrupole gradient, T/m	20.833
Quadrupole component ampere-turns, A	Iw_q= 26828
Sextupole strength, T/m^2	375
Sextupole component ampere-turns, A	21728.5
Total conductor current at all component max field, A	50-80
Maximum flux density in the yoke at max field, T	2.0

TABLE 6

MAIN FIELD: -0.39884 NORMAL REL. MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	13267.87286	b 3:	6003.10682
b 4:	0.00000	b 5:	0.66167	b 6:	0.02465
b 7:	-0.11591	b 8:	0.00000	b 9:	-76.02892
b10:	-36.19108	b11:	-5.46565	b12:	0.00000
b13:	-0.97866	b14:	-1.06235	b15:	-0.26914
b16:	0.00000	b17:	-0.00005	b18:	0.00002

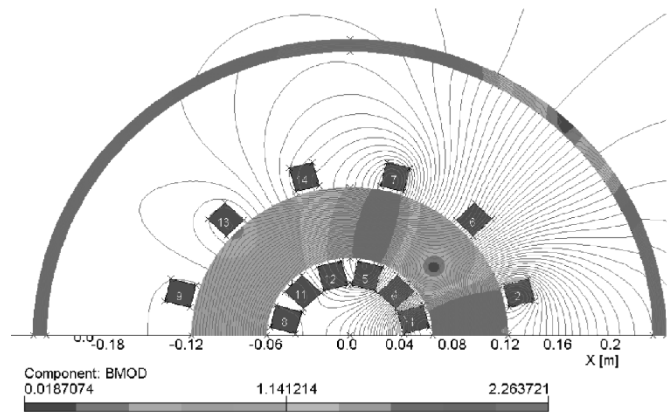

Fig. 5. Corrector C flux density distribution at maximum coil currents.

The cold mass assembly is rotated on 15º as shown on Fig.5. The magnet design is the same as for A and B correctors. Magnetic field, currents and forces are symmetrical relatively magnet median plane, that is why only 5 independent power supplies needed to power this type corrector.

III. MECHANICAL DESIGN CONCEPTS

There are at least two options of cold mass fabrication and assembly. The first one is to wind all racetrack coils separately on the aluminum or stainless steel bobbins, then assemble two sub assemblies with the 6 coils each. In this case the iron core should be splitted in the median plane. After that cold mass should be vacuum impregnated with epoxy. The second version is to split the iron core on 4 or 12 sectors and use these parts as mandrel for coil winding, impregnation and support. In this case each iron block with one coil can be tested separately. Because at all field combinations the iron blocks are tightened to each other, only positioning pins needed to provide proper block position in space. Special attention needed to provide the tight coil bobbin connection to the yoke because at some currents combination will be Lorentz forces directed inside the magnet aperture. There will be also the cold mass decentering forces. Decentering force for correctors A and B rather low (160 kg) and for corrector C higher (1900 kg). So, the cold mass support structure should be capable carry this load plus the magnet weight (~500kg).

Aluminum and stainless steel bobbin material should be compared. Aluminum can provide the coil prestress after cooling down but stainless steel can be welded to the iron yoke and that simplify the magnet assembly. Usual machining tolerances are acceptable and the machining cost will be low.

IV. Electrical Circuits, Currents and Power Supplies

The electrical connections are very simple for this type of magnet. Each coil should be connected to pair of current leads capable to carry ~80 A current. All coil to coil connections can be made outside the magnet before or during operation if universal type multipole will be chosen. Individual bipolar power supplies should power all current leads outer connectors. It is possible to reduce the number of currents and power supplies to 5 in the case of normal dipole, quadrupole and sextupole fields (see Table 7).

Table 7

Corrector Type	Max coil ampere-turns, A	Number of PS/magnet	Max coil current at 760 turns/coil, A
A (HD+VD+SQ)	33000	10	43.4
B (VD+SQ)	25400	5	33.4
B (HD+SQ)	25400	5	33.4
C (VD+Q+S)	58413	5	76.8
C (HD+Q+S)	58413	10	76.8

The coil current is the sum of all components, which produce the dipole, quadrupole and sextupole fields. The current directions for different normal field components are shown on Fig. 3. Skew fields can be obtained by the angular rotation of corresponding multipole ring diagram.

The coil current can be reduced if decrease the superconducting wire diameter and proportionally increase number of turns. Conductor diameter, number of turns and max current should be simultaneously optimized with reasonable quench current margin and mechanical stability. There is about two times difference in max currents for A,B and C magnets. It is possible to reduce the volume of superconductor for A and B correctors proportionally increasing the current.

It should be noted that at the magnet ends will be larger magnetic field and correspondingly lower current margin. This effect can be reduced by proper profiling coils and yoke at the ends.

The overview of designed and tested superconducting correctors showed that in most magnets the operating current was chosen with large margin (see Table 8). During fabrication some of the magnets failed to pass the high voltage test because of weak enamel insulation and short-circuits between turns and to the ground. Proposed BTeV variants of multipole corrector are placed in BTeV column of Table 8.

Table 8

Parameter	FNAL	RHIC	UNK	LHC	BTEV
Dipole field, T	0.62	0.58	0.59	0.11	0.6 max
Quadrupole gradient, T/m	9.84	2.72	4.37	60	20.8 max
Sextupole strength, T/m^2	294.5	-	448		375
Operating current, A	50	50	20	100	35-77
Critical current @ 4.2K, 5T, A	160	130	54-69	228	160
Coil maximum field, T	1.5	-	1.3	3 -3.22	1.7
Coil inner diameter, mm	80	82.1	80	90	80
Outer cold mass diameter,mm	152		168	242	290
Conductor diameter, mm	0.5	0.33	0.3	0.5	0.5
Strand current density, A/mm^2	255	585	283	510	255
Cu/NbTi ratio	-	2.5	1.7	2.0	2.0
Jc @ 4.2K, 5T, A/mm^2	-	-	2000	3165	2200
Length, m	0.77	0.5	1.37	0.52	0.8 - 1.2

V. Conclusion

Proposed variant of multipole corrector has the following advantages:

- only one type of multipole magnet which cover all needs
- possibility to generate any combination of dipole, quadrupole and sextupole normal and skew fields
- stable magnetic center and field quality
- simple coil manufacturing
- only two magnet types with 0.8 m and 1.2 m length
- no inner splices
- good mechanical stability because of eliminating opposite forces in coils
- good coil cooling
- possibility of individual coil block test and training
- simple tooling
- easy assembly, disassembly and repair
- low labor.

The chosen current density for these correctors are rather conservative. It can be increased only after the prototype tests and in most defined by better for this type magnet mechanical stability and cooling.

References

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